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AN ACOUSTIC IMPEDANCE INVERSION APPROACH TO DETECT AND CHARACTERIZE GAS HYDRATE ACCUMULATIONS WITH SEISMIC METHODS: AN EXAMPLE FROM THE MALLIK GAS HYDRATE FIELD, NWT, CANADA

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ABSTRACT

Two internationally-partnered research well programs, in 1998 and 2002, studied the Mallik gas hydrate accumulation in the Mackenzie Delta, Canada. Gas hydrate bearing intervals were cored, logged and production tested thus establishing Mallik as an excellent site for testing geophysical imaging techniques. Here, we apply a model-based acoustic impedance inversion technique to 3D seismic reflection data acquired over the Mallik area to characterize gas hydrate occurrences and to help define their spatial extent away from well control. Sonic logs in Mallik research wells show that P-wave velocity of sediments increases with hydrate saturation, enough to produce detectable reflections for the lower two of three known gas hydrate zones. The inversion method converts these reflections into acoustic impedances from which velocity and hydrate saturation can be estimated. Acoustic impedance inversion results indicate that the deepest gas hydrate zone covers an area of approximately 900,000 m^2. With some assumptions on the lateral continuity of gas hydrate saturation, porosity and thickness measured at the wells, we estimate that this zone contains approximately 771×10^6 m^3 of gas at standard atmospheric pressure. At a regional scale, results allowed the detection of a high-velocity area near the A-06 well, about 6 km south-east of 5L-38. We infer that the high velocity area corresponds to a gas hydrate accumulation. Logging data in A-06 indicate the presence of gas hydrates in this area and support our interpretation.

Keywords: gas hydrates, acoustic impedance inversion, seismic, Mallik

INTRODUCTION

Seismic methods play a significant role in assessing and characterizing in-situ marine and permafrost-related gas hydrate deposits. Estimated volumes obtained from seismic characterization studies help to provide realistic assessment of the

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potential impacts of gas hydrates on global climate change, as a geohazard or future energy resource. Gas hydrates have distinctive physical properties that allow their detection on seismic records. Poorly consolidated sediments with gas hydrates located in their pore space are stiffer and exhibit higher P-wave velocity that generally increases the acoustic impedance (product of density and velocity). The contrast of acoustic impedance between hydrate-bearing sediments and those without gas hydrates is often sufficient to produce a strong seismic reflection [1; 2]. Reflectivity is even stronger when gas hydrates are in contact with low-velocity sediments with free gas at the base of the stability field. The resulting Bottom Simulating Reflector (BSR) is commonly used to infer their presence in marine environment.

Acoustic impedance inversion methods [3] are frequently used to convert seismic reflections occurring at layer boundaries into acoustic impedances associated with the sedimentary units straddling these boundaries. The results can be linked directly to rock-properties measured in well-logs thus providing distribution of acoustically-distinctive units. Previous acoustic impedances obtained from a band-limited inversion of seismic data have shown the applicability of this approach to gas hydrates [4]. A fundamental but yet realistic assumption is that high acoustic impedances are indicative of gas hydrates in poorly consolidated sediments. Here, we present acoustic impedances and velocity estimates obtained with a model-based inversion [3] of 3D seismic data from the Mallik area, Northwest Territories (Figure 1). The model-based inversion provides improved correlation at well locations and defines more accurately the resource in place. Inversion results are also used at a regional scale to help identify areas of high acoustic impedance that may indicate the presence of hydrate. We identified one of these probable hydrate areas near the A-06 well site.

GEOLOGICAL SETTING

The 3D seismic data used in this study is located in the western part of Richards Island in the Mackenzie River Delta on the coast of the Beaufort Sea (Figure 1). The area straddles two physiographic regions identified by Rampton [5], the Big Lake Delta Plain to the west which is influenced by active Mackenzie River deltaic deposition and older upland terrain referred to as the Tuktoyaktuk Coastlands. Pleistocene sediments consisting mainly of glacial, marine and fluvio-deltaic sediments are exposed at shallow depth beneath the Big Lake Delta plain and outcrop at the surface in the Tuktoyaktuk Coastlands. These deposits are underlain by older deformed deltaic Tertiary strata [6].

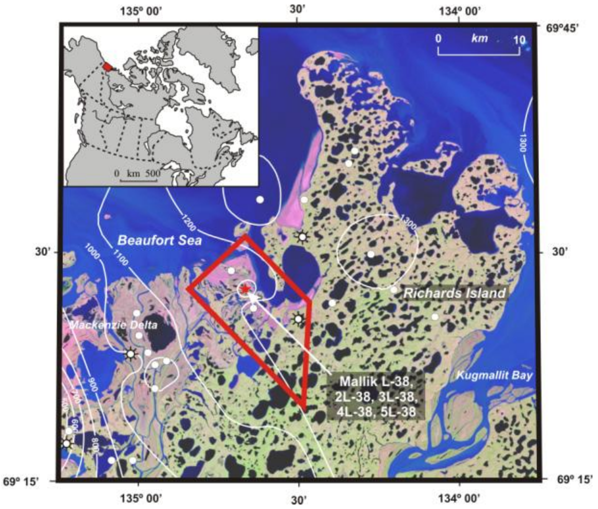

Figure 1. Location of the JAPEX/JNOC/GSC et al. Mallik gas hydrate research wells in the Mackenzie Delta (modified from Dallimore and Collett, 2005). The red polygon outlines the area covered by the 3D seismic survey used in this study. Small circles indicate well locations and larger circles with ticks show wells that intersected gas hydrate. Contours represent the base of the gas hydrate stability field as determined by Majorowicz and Smith (1999).

Interpretations of geophysical well logs from exploration wells in the area suggest that ice bonded permafrost beneath terrestrial areas is 600 to 650 m deep and that gas hydrates can occur to depths of 1150 m [7]. Two major gas hydrate research well programs have been conducted at the Mallik site [8] which is located at the apex of a regional anticline structure. Core studies and geophysical interpretations document that gas hydrate occurs in coarse-grained sandy sediments of the Mackenzie Bay and Kugmalit Tertiary sequences from 870 to 1100 m depth. The gas hydrate-bearing sediments are interbedded with silty sediments with little or no gas hydrate. The gas hydrate intervals (zone A, B and C on Figure 2) are up to 40 m thick and have high gas hydrate saturation, sometimes exceeding 80% of pore volume of unconsolidated clastic sediments with average porosities ranging from 25% to 40%.

MALLIK SEISMIC DATA

We use the upper two seconds of a 3D seismic reflection data set acquired and processed by Veritas DGC Land in 2002. This data set has been made available to the Mallik 5L-38 science program through partnership with the BP-Chevron/Texaco-Burlington joint venture parties. The area covered by the Mallik 3D includes four gas hydrate targeted wells (2L-38, 3L-38, 4L-38 and 5L-38) and four industry wells drilled by Imperial Oil Limited in the 1970s (L-38, P-59, J-37 and A-06). The 3D acquisition geometry was designed to image conventional hydrocarbon accumulations located beneath the gas hydrate zones (deeper than 1100 m). The processing also focussed on the imaging of the conventional gas-bearing structures rather than gas hydrates, and so the resulting 3D volumes provide poor images of the permafrost (<600 m) and low common-depth-point fold in the gas hydrate depth range. Low fold results partly from strong mutes applied to remove surface waves that cover and dominate useful seismic signal. From the differently processed data sets available for the Mallik 3D, we selected one that preserved the relative true-amplitude character of the data. This is particularly critical to obtain meaningful acoustic impedances.

Sonic and density logs acquired in 2L-38 and 5L-38 were used to assess seismic ties at well locations. Strong correlation at the well is fundamental to the evaluation of the spatial extent of hydrate zones around the Mallik wells from seismic data. Synthetic seismic traces from 5L-38 logs were compared to traces from the 3D data set near the well (Figure 2). A time-to-depth conversion curve was obtained from direct arrival traveltimes measured on a zero-offset VSP acquired in 2L-38 [9]. Synthetic seismic traces for vertical incidence were calculated by convolving the reflection coefficients obtained from the sonic and density logs with a wavelet extracted from the 3D data using a frequency matching approach. The extracted wavelet is zero-phase and has frequencies ranging between 20 and 75 Hz.

In general, synthetic traces from the 3D survey show positive amplitude peaks at the top and troughs at the base of gas hydrate zones A, B and C (Figure 2). The synthetic traces also predict a reflection in the middle of zone B corresponding to higher velocities in this interval. The seismic traces extracted from the 3D data set close to 5L-38 reveal strong and continuous troughs at the base of horizons B and C (Figure 2). These two reflections represent excellent markers to determine the spatial extent of the gas hydrate zones. These traces also show a second peak within zone B that could correspond to the middle reflection on the synthetic traces; however, correlation with the synthetic traces for that reflection is less convincing. The 3D and synthetic traces do not correlate well in the time range corresponding to zone A, likely due to inadequate imaging of this zone on the real data.

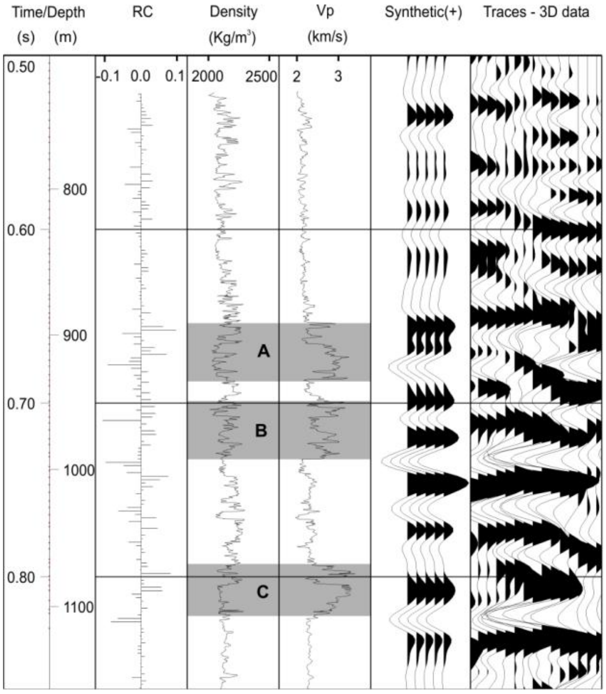

Figure 2. Synthetic modeling at 5L-38 using the 3D wavelet and the Mallik 5L-38 density and P-wave sonic logs. Obvious data spikes were removed manually from the logs. Traces were extracted from an EW-section of the 3D data set through 5L-38. Time/depth conversion curve was derived from first-arrival traveltimes from a zero-offset VSP at 2L-38 (Sakai, 1999). Reflection coefficients (RC) were calculated from the density and P-wave velocity (Vp) logs.

ACOUSTIC IMPEDANCE INVERSION

Mallik area

A model-based inversion [3] was used to extract acoustic impedances from the true-amplitude seismic data around the Mallik wells. This inversion approach requires an initial model of the acoustic impedance defining low-frequency trends that cannot be recovered by seismic data alone, but that are critical to obtain realistic properties. We tested two starting models based on P-wave and density logging data. The models consist of a low-frequency (1 Hz) and slightly higher frequency (10 Hz) filtered versions of the logging data in 2L-38 (Figure 3). The 10 Hz model has higher impedances within gas hydrate zones but they do not reach the maximum expected from the logs. The 1 Hz model is primarily a non gas-hydrate starting model with a steady increase of velocity with depth. The two low-frequency acoustic impedance trends were then extended laterally from the well following the seismic trough at the base of the gas hydrate zone C. The inversion is run with a constraint that maintains the final solution within ±25% of the initial model. Figure 3 shows inverted acoustic impedances for both starting models. Due to the inversion constraint, impedances are slightly underestimated within the hydrate interval, especially for the 1 Hz model.

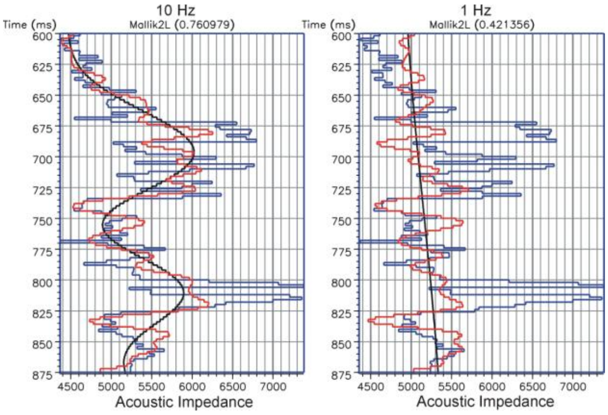

Figure 3. Acoustic impedance inversion results at 2L-38 for the 1Hz and 10 Hz starting models (black line). The blue lines show the measured acoustic impedances whereas the red lines show the inverted acoustic impedances. Numbers in parenthesis are the correlation coefficients between inverted and measured impedances for the 600-875 ms interval.

We extracted P-wave velocities from the impedances assuming no vertical and lateral variability in the density of the sediments. The density is relatively constant throughout the entire gas hydrate range and averages 2100 kg/m^3. This value was used to convert the acoustic impedances to velocity. Figure 4 shows a comparison of P-wave velocity at the C gas hydrate horizon obtained with the 1 Hz and 10 Hz initial models. Both inversions did not recover exactly the high velocities measured on borehole logging data but they show increasing P-wave velocities over the gas hydrate zones. The constraints used in the inversion explain the overall lower P-wave velocities recovered with the 1 Hz model (Figure 4), as this model does not include effects from the individual gas hydrate layers. The inversion results obtained with the 10 Hz model suggests a laterally extensive gas hydrate distribution around the Mallik wells. An area of approximately 900,000 m^2 comprises P-wave velocity higher than 2900 m/s (Figure 4). From this geographic distribution, we estimate a volume of 4.7x10^6 m^3 of gas hydrate or 771x10^6 m^3 of gas at atmospheric pressure conditions for zone C. This is based on a thickness of 25 m, a porosity of 0.35, a gas hydrate saturation of 0.6 (determined from an empirical relationship between Vp and gas hydrate saturation) and an occupancy ratio of 100%. This remains a crude volume estimate as saturation, thickness and porosity values are not uniform over the inverted area. The P-wave velocity obtained with the 1 Hz initial model show a rather patchy distribution (approximately 180,000 m^2 with Vp higher than 2900 m/s) and suggest a lower gas hydrate volume. In our opinion, results from the 10 Hz model provide a more realistic volume estimate simply because inverted P-wave velocity near the wells are closer to sonic log values. It is important to note that both inversion results reveal in general similar structures but with different intensity (e.g. Vp scaled differently).

Looking outside the Mallik area

The 1 Hz model follows the natural increase of velocity with depth and is not biased by high-impedances corresponding to gas hydrate intervals in 2L-38. This unbiased characteristic makes it a suitable model to search for new hydrate bearing areas outside the Mallik well site. Thus, we have chosen to invert the entire 3D seismic data with the 1 Hz model. Because of the inversion constraints, we expect that the inverted results will underestimate velocity of gas hydrate and provide conservative saturation estimates. Similarly to the Mallik well area, we produced approximate P-wave velocity maps by dividing the inverted impedances with a constant density of 2100 kg/m^3.

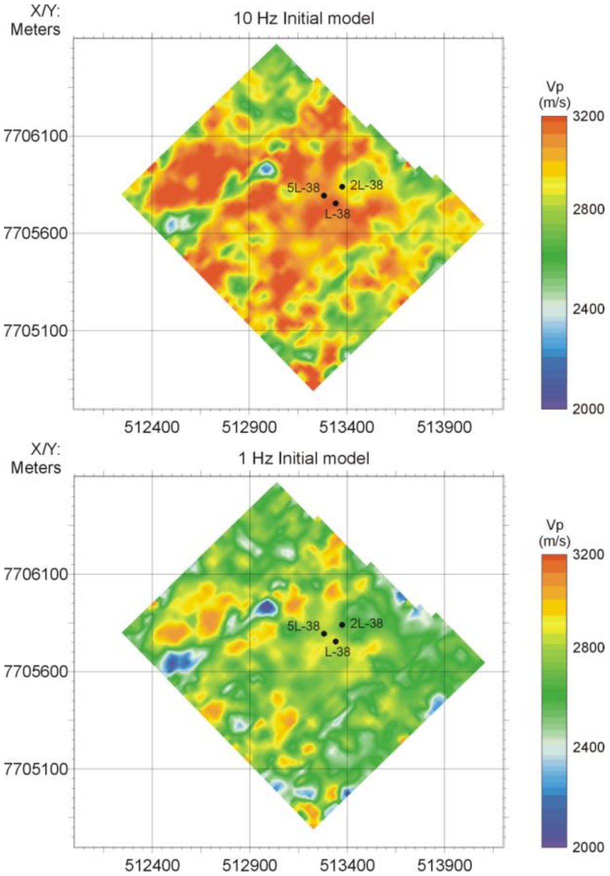

Figure 4. Comparison of P-wave velocity at the C gas hydrate horizon (e.g. following this horizon) obtained with the 1 Hz and 10 Hz initial models.

Figure 5 shows one of the P-wave velocity maps near the A-06 well site, about 6 km south-east of Mallik. In the northwest part of Figure 5, a high-velocity zone covering an area of ~200,000 m^2 with P-wave velocity higher than 2900 m/s is evident. Figure 5 is a time slice at 0.812s, which is close to the expected base of the gas hydrate stability zone. We infer that the high velocity area may indicate a gas hydrate accumulation. Sonic logs from A-06 located approximately 2 km ESE of the high-velocity zone indicate the presence of hydrates in this area and free gas below the base of the stability field (Figure 6). A thin layer of the Lower Richards Formation containing free gas was intersected at a depth of approximately 2.5 km in A-06. Part of this free gas may have been the source of the inferred gas hydrate accumulation near A-06, and migrated along faults to form hydrates in the shallower strata.

CONCLUSIONS

We applied a model-based acoustic impedance inversion technique to 3D true-amplitude seismic

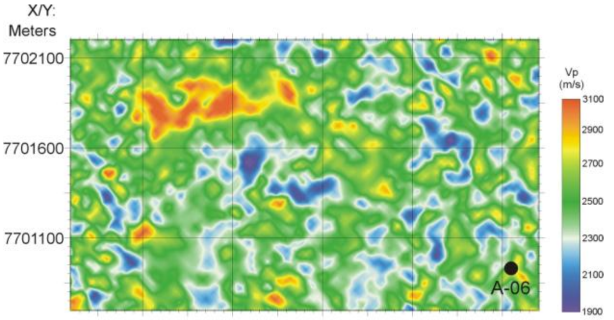

Figure 5. Time slice at 0.812 s showing the P-wave velocities obtained from acoustic impedance inversion. An area of high velocity is mapped approximately 1750 m NW of well A-06.

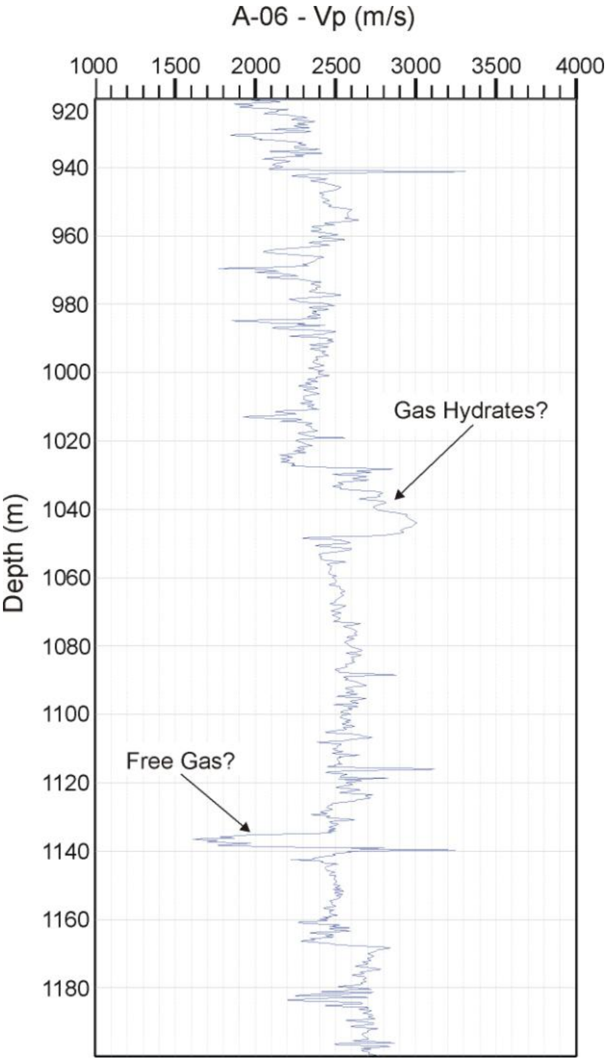

Figure 6. Sonic logging data from well A-06 showing a potential interval of gas hydrate between 1030-1050 m and a thin free gas layer at 1137 m.

reflection data acquired over the Mallik area to characterize gas hydrate occurrences and to help define their spatial extent away from the wells. Of the two initial models tested, the 10 Hz model provides the most accurate velocity map and volume estimate of gas hydrates near the Mallik wells. The 1 Hz model is more appropriate to search for other gas hydrate accumulation outside the Mallik well area. Results obtained with both models underestimate P-wave velocities, especially the 1 Hz starting model. Acoustic impedance inversion results indicate that the deeper gas hydrate zone (zone C) near 5L-38 covers an area of approximately 900,000 m^2. With some assumptions on the lateral continuity of saturation, porosity and thickness measured at the wells, we estimate that this zone contains approximately 771×10^6 m^3 of gas at standard atmospheric pressure. At a regional scale, results allowed the detection of a high-velocity area near the A-06 well. We infer that the high velocity area corresponds to a gas hydrate accumulation. Logging data in A-06 indicate the presence of gas hydrates in this area and support our interpretation.

ACKNOWLEDGMENTS

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